

*THE GENERALIZED MATCHING LAW DESCRIBES
CHOICE ON CONCURRENT VARIABLE-INTERVAL
SCHEDULES OF WHEEL-RUNNING REINFORCEMENT*

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Six male Wistar rats were exposed to concurrent variable-interval schedules of wheel-running reinforcement. The reinforcer associated with each alternative was the opportunity to run for 15 s, and the duration of the changeover delay was 1 s. Results suggested that time allocation was more sensitive to relative reinforcement rate than was response allocation. For time allocation, the mean slopes and intercepts were 0.82 and 0.008, respectively. In contrast, for response allocation, mean slopes and intercepts were 0.60 and 0.03, respectively. Correction for low response rates and high rates of changing over, however, increased slopes for response allocation to about equal those for time allocation. The results of the present study suggest that the two-operant form of the matching law can be extended to wheel-running reinforcement. The effects of a low overall response rate, a short changeover delay, and long postreinforcement pausing on the assessment of matching in the present study are discussed.

Key words: matching law, concurrent variable-interval reinforcement schedules, wheel-running reinforcement, lever press, rats

In 1961, Herrnstein formulated a principle of choice known as the matching law. According to this molar theory of choice, organisms allocate behavior between concurrently available sources of reinforcement so as to match the relative rates of reinforcement obtained from those alternatives. Expressed as an equation, the matching law appears as follows:

$$\frac{B_L}{B_L + B_R} = \frac{R_L}{R_L + R_R}, \quad (1)$$

where B_L and B_R refer to responses or time allocated to left and right alternatives, and R_L and R_R refer to reinforcers obtained from these alternatives.

Baum (1974b) reformulated Equation 1 to accommodate systematic deviations from matching. This reformulated version of the matching law equation is known as the generalized matching law and appears as follows:

$$\log (B_L/B_R) = a \log (R_L/R_R) + \log b, \quad (2)$$

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where the coefficient a is the slope of the line relating behavior to reinforcer allocation, and $\log b$ is the intercept of that line on the ordinate. Values of the slope and intercept are interpreted as sensitivity to differences in rates of reinforcement between the alternatives and bias toward an alternative that is not related to relative reinforcement.

In the decades since its formulation, the generalized matching law has been shown to describe choice across a variety of species, responses, and reinforcers. For example, matching has been demonstrated with rats (Baum, 1976; Graft, Lea, & Whitworth, 1977; Norman & McSweeney, 1978; Poling, 1978), pigeons (Baum, 1973, 1974a; Davison & Hunter, 1976; Herrnstein, 1961; Hunter & Davison, 1978; Marcucella & Margolius, 1978), domestic hens (Sumpter, Temple, & Foster, 1998; Temple, Scown, & Foster, 1995), cows (Foster, Temple, Robertson, Nair, & Poling, 1996; Matthews & Temple, 1979), monkeys (Iglauer & Woods, 1974), and humans (Baum, 1975; Bradshaw, Szabadi, & Bevan, 1979; Bradshaw, Szabadi, Bevan, & Ruddle, 1979; Buskist & Miller, 1981; Madden & Perone, 1999; Pierce & Epling, 1983; Savastano & Fantino, 1994; Takahashi & Iwamoto, 1986). Allocation of behavior such as lever pressing (Iglauer & Woods, 1974; Norman & McSweeney, 1978), key pecking (Herrnstein, 1961; Logue, 1983), eye movements (Schroe-

der & Holland, 1969), conversation (Conger & Killeen, 1974), and button pressing (Bradshaw, Szabadi, & Bevan, 1979) has been described using the matching law. Finally, studies of matching have involved different reinforcers such as food (Marcucella & Margolius, 1978; Matthews & Temple, 1979), points exchangeable for money (Bradshaw, Szabadi, & Bevan, 1979; Bradshaw, Szabadi, Bevan, & Ruddle, 1979; Savastano & Fantino, 1994), drugs (Iglauer & Woods, 1974; Woolverton & Alling, 1999), shock avoidance (Baum, 1973; Hutton, Gardner, & Lewis, 1978; Logue & de Villiers, 1981), water (McSweeney, Swindell, & Weatherly, 1996; Zimmerman, 1969), sexual stimuli (Cliffe & Parry, 1980), and electrical brain stimulation (Holland & Davison, 1971).

In 1994, Belke and Heyman extended the single-operant or hyperbolic form of the matching law to wheel-running reinforcement. This single-operant matching law, formulated by Herrnstein (1970), describes choice in a context in which there is only a single source of reinforcement arranged by the experimenter and a single measured response. In this context, the relation between rates of lever pressing and reinforcement takes the form of a hyperbola described by the following equation:

$$B_1 = \frac{kR_1}{R_1 + R_e}, \quad (3)$$

where B_1 is the predicted response rate and R_1 is the obtained reinforcement rate. The parameters k and R_e are fitted and estimate the response-rate asymptote and the reinforcement rate that maintains a response rate equal to one half of the response-rate asymptote, respectively. Theoretically, this form of the matching law describes allocation of behavior between the measured response and any other behavior in the context.

Belke and Heyman (1994) exposed rats to a sequence of tandem fixed-ratio (FR) 1 variable-interval (VI) schedules within the same session. The VI component of the tandem schedules varied across the following order of schedule values: VI 60, VI 15, V 5, VI 7.5, and VI 30 s. The reinforcer was an opportunity to run for 60 s. Equation 3 was fitted to response

and reinforcement rates obtained for each session. The results showed that the relation between response and reinforcement rates was well described by the single-operant form of the matching law.

Belke (2000), however, recently showed that within-session changes in running and lever-pressing rates are problematic for this form of the matching law. Estimates of k and R_e varied systematically with schedule order, and the differences between the estimates were highly correlated with the magnitude of increases in lever-pressing rates between the beginning and the end of a session when reinforcement rate was held constant. Consequently, although the response-reinforcer relation with wheel-running reinforcement may be well described by Equation 3, estimated parameters of this equation change when the efficacy of the reinforcer changes markedly within a session.

One way to surmount this problem is to use the two-operant form of the matching law. With the two-operant form, the dependent measure is the allocation of behavior between alternatives rather than the absolute rate of responding on a single alternative. Consequently, any change in reinforcer efficacy within a session affects both alternatives equally. Thus, the distribution of behavior between these alternatives should be less susceptible to the within-session effect. The present study sought to determine if the generalized matching law could be used to describe choice between alternative sources of wheel-running reinforcement.

METHOD

Subjects

Six male Wistar rats obtained from Charles River Breeding Laboratories served as subjects. When not in the experimental apparatus, rats were individually housed in standard polycarbonate cages (48 cm by 27 cm by 22 cm) in a colony room maintained at 20 °C with a 12:12 hr light/dark cycle (lights on at 8:00 a.m.). Subjects were maintained at target weights that were approximately 80% of free-feeding weights taken when their weights rose just above 400 g (i.e., adult weight). As a result, target weights varied around 320 g \pm 10 g. Animals were maintained on food re-

striction because previous research has shown that the tendency to run varies inversely with body weight. Distilled water was freely available in the home cages.

Apparatus

Subjects were tested in two Wahman activity wheels (35.5 cm) without side cages. Each wheel was located in a sound-attenuating shell equipped with a fan for ventilation and to mask extraneous noise. A solenoid-operated brake was attached to the base of each wheel. When the solenoid was operated, a rubber tip attached to a metal shaft contacted the outer rim of the wheel and brought the wheel to a stop. A microswitch attached to the wheel frame recorded wheel revolutions. Lights (24-V DC) mounted on the sides of the wheel frame served to illuminate the inside of the wheel chamber.

A Plexiglas panel holding two response levers, two stimulus lights, and a solution receptacle was attached to the wheel frame by Velcro®. The levers were 1.5 cm wide and extended 2 cm out from the surface of the panel. The force required to activate a lever ranged between 31 and 33 g. The levers were located 13 cm from the base of the panel and were separated by 4.5 cm. The solution receptacle was located in the space between the two levers. Yellow stimulus lights were located 0.7 cm above each lever. When the panel was attached to the wheel, the levers extended through an opening (7 cm by 9 cm) to the wheel and were 7.5 cm above the floor of the wheel. Control of experimental events and recording of data were handled by IBM® personal computers interfaced to the wheels through their parallel ports.

Procedure

The 6 rats were first trained to press a lever on schedules of reinforcement with the opportunity to run as a reinforcer in a different set of wheels that were equipped with retractable levers. The training phase began with a procedure for the selection of rats with a tendency to run sufficient for training them to press a lever for the opportunity to run. Each rat was placed in a running wheel for a daily 30-min session for 10 days. The number of wheel revolutions was recorded for each rat on each day. After 10 days, rats, including those used in the present study, were selected

based on the criterion of running rates in excess of 10 revolutions per minute.

Training the animals to press a lever for the opportunity to run began by shaping lever pressing with sucrose reinforcement in standard operant conditioning chambers. Sessions in the operant conditioning chambers occurred following the 30-min wheel-running period each day. In these sessions, each lever press produced 0.1 ml of a 15% sucrose solution. When subjects reliably pressed the lever, the schedule of reinforcement was changed from FR 1 to variable-ratio (VR) 3. This schedule remained in effect for approximately four sessions, with each session terminating when 50 sucrose reinforcers had been obtained.

After four sessions on the VR 3 schedule, sessions in the operant conditioning chamber were discontinued. At this point, a retractable lever in each training wheel was extended during the wheel-running sessions, and the opportunity to run for 60 s was made contingent on a single lever press. When a press occurred, the lever retracted and the brake released, leaving the wheel free to turn for 60 s. Once 60 s had elapsed, the reinforcement period was terminated by the application of the brake, and the lever was extended. Each session consisted of 30 opportunities to run. The schedule of reinforcement was changed in the following sequence: FR 1, VR 3, VR 5, VR 9, and VR 15. Each schedule remained in effect for four sessions.

Following this training, the animals were transferred from the wheels in which they were trained to the wheels equipped with two levers for the present study. To prepare the animals for responding on concurrent schedules and to facilitate the transfer of their training to the new wheels, the animals were first exposed to sessions with only the left or the right lever operative. For these sessions, the stimulus light above the operative lever was illuminated, and the schedule of reinforcement was VI 30 s. The reinforcer was the opportunity to run for 15 s. When the programmed interval elapsed and a response occurred on the operative lever, the stimulus light was extinguished and the brake was released, leaving the wheel free to turn for 15 s. After 15 s, the brake was enabled and the stimulus light was illuminated. During the session, the 24-V DC lights attached to the wheel

Table 1

Order of presentation of concurrent variable-interval schedules for each rat.

Rat	Concurrent			
	VI 60 s VI 60 s	VI 48 s VI 72 s	VI 80 s VI 40 s	VI 30 s VI 90 s
TL 3	2	3	4	1
TL 8	3	2	1	4
TL 11	1	3	2	4
TL 16	4	2	3	1
TL 19	4	1	2	3
TL 26	1	4	3	2

frame illuminated the wheel chamber. Each animal was exposed to five sessions with the left lever operative and then five sessions with the right lever operative. Following this the animals were exposed to a concurrent VI 30-s VI 30-s schedule for 10 sessions prior to commencing the series of concurrent VI VI schedules used in the present study. Each VI schedule was composed of 10 intervals that approximated an exponential distribution (Fleshler & Hoffman, 1962). Table 1 shows the schedule order for each rat. A change-over delay (COD) of 1 s was in effect to diminish the reinforcement of switching between alternatives. The short duration of the COD was chosen at this stage because several rats were not obtaining reinforcement on both alternatives. Session duration was increased to 45 min.

Each schedule remained in effect until three stability criteria were met. First, a minimum of 25 sessions had to occur before performance could be judged stable. Second, the difference between the highest and the lowest response proportion over 5 consecutive days had to be equal to or less than 0.05. Third, there could be no trend in the response proportions over the last three sessions. When these three conditions were met, performance was judged to be stable.

Lever presses to, time spent on, changeovers to, and reinforcers obtained from each alternative were recorded during each session. Time on an alternative was defined by changeovers. An animal was defined as being on an alternative and time was cumulated until a response was made on the other alternative. Time spent with access to the reinforcer was subtracted from time measured in this manner to arrive at the measure of time

on an alternative. In addition, revolutions during reinforcement periods for each alternative were recorded. Time and response matching were assessed using Equation 2.

RESULTS

Average responses, time, changeovers, reinforcers, and revolutions associated with each alternative for the five sessions that met the stability criteria as well as the number of sessions to stability for each schedule for each animal are presented in Table 2. Figure 1 shows the relation between log response ratios and log reinforcer ratios as described by Equation 2 for each animal. In general, response allocations undermatched obtained reinforcer ratios. Slopes ranged from 0.44 to 0.82, with a mean of 0.60. Intercepts ranged from -0.21 (i.e., a bias toward the right lever) to 0.27 (i.e., a bias towards the left lever), with a mean of 0.03 . Finally, estimates of variance accounted for ranged from 83% to 99%, with a mean of 94%.

Figure 2 shows the relation between log time ratios and log reinforcer ratios for each animal. Although time allocation also undermatched reinforcer ratios, the degree of undermatching was much less. Slopes ranged from 0.53 to 1.03, with a mean of 0.82. Intercept values ranged from -0.09 to 0.07 , with a mean of 0.008 . Estimates of variance accounted for ranged from 97% to 99%, with a mean of 98%. Differences between slope and intercepts for time and response allocation were assessed using a paired t test. Slopes for time allocation were significantly greater than those for response allocation, $t(5) = 3.77$, $p < .05$, but intercepts did not differ, $t(5) = -0.29$, $p > .10$.

Figure 3 depicts log response and log time ratios as a function of log reinforcement ratios for the group. For response ratios, regression on reinforcement ratios yielded values for slope, intercept, and percentage of variance accounted for of 0.56, 0.04, and 59%, respectively. For time ratios, an equivalent analysis yielded values of 0.86, 0.005, and 94%, respectively. Slope and intercept were similar to the means of the estimates for individual rats. The estimate of variance in log time ratios accounted for was also similar; however, the percentage of variance in response ratios accounted for was markedly

Table 2

Mean responses, time (in seconds), reinforcers, changeovers (CO), and revolutions per reinforcer for the left (L) and right (R) alternatives for each concurrent VI schedule for each rat. Sessions (S) to stability for each schedule are also provided.

Rat	VI		S	Responses		Time		Reinforcers		CO		Revolutions	
	L	R		L	R	L	R	L	R	L	R	L	R
TL 3	60	60	37	213.4	195.4	1,003.2	960.8	23.8	23.0	58.6	58.8	8.9	8.8
	48	72	29	290.4	145.0	1,298.8	658.1	33.5	15.2	63.2	63.4	8.8	8.6
	80	40	57	238.0	250.4	901.2	992.6	21.6	30.2	73.6	73.2	9.2	8.9
	30	90	27	250.2	95.2	1,456.1	378.5	45.2	12.0	33.6	33.6	8.6	8.8
TL 8	60	60	31	372.2	245.8	1,115.3	886.5	24.2	19.2	115.6	115.4	11.1	11.8
	48	72	30	356.2	224.6	1,142.8	882.3	26.6	17.6	104.4	104.8	11.2	10.7
	80	40	35	213.2	239.4	759.3	1,185.9	16.8	30.6	82.0	82.0	10.3	10.2
	30	90	38	307.4	137.2	1,393.1	546.6	36.2	11.8	79.2	79.4	10.7	11.3
TL 11	60	60	41	185.0	199.0	1,060.2	1,010.2	20.2	20.0	56.6	56.8	10.7	10.4
	48	72	31	178.4	132.2	1,219.1	842.7	25.6	15.6	40.4	40.6	11.2	11.3
	80	40	28	157.8	202.0	719.7	1,311.3	14.8	28.2	46.4	46.6	9.9	9.8
	30	90	43	169.0	71.8	1,527.2	441.7	37.0	8.4	25.8	26.0	12.2	12.0
TL 16	60	60	42	196.6	264.6	753.5	1,173.8	21.4	23.6	60.8	61.4	13.0	12.2
	48	72	29	354.4	209.2	1,178.9	733.7	32.4	17.2	59.0	59.4	14.0	14.0
	80	40	41	195.4	319.8	638.8	1,245.1	18.2	31.6	67.8	68.4	14.1	13.6
	30	90	57	184.8	133.2	1,333.9	523.1	39.2	13.4	33.4	33.2	13.1	13.1
TL 19	60	60	25	149.8	142.2	1,368.8	654.8	25.6	16.2	36.4	36.4	9.0	8.9
	48	72	32	183.4	234.6	1,299.8	684.2	28.8	16.2	46.4	47.0	8.9	9.3
	80	40	25	158.8	345.0	804.5	1,097.6	20.2	30.4	67.8	68.0	9.0	9.2
	30	90	30	144.2	54.2	1,600.8	347.5	41.0	7.4	16.4	16.4	6.8	7.0
TL 26	60	60	25	803.8	493.2	970.2	917.8	26.8	26.8	208.8	209.2	11.8	11.7
	48	72	25	1,014.6	430.4	1,076.7	794.1	32.2	22.8	172.0	172.2	10.7	10.9
	80	40	27	650.8	428.4	808.7	1,026.4	21.2	36.2	157.4	157.4	10.6	10.5
	30	90	25	1,058.8	367.0	1,126.9	626.2	46.2	16.4	197.4	197.2	11.3	11.6

lower for the group than for individual data. This suggests greater differences among individuals with respect to response allocation.

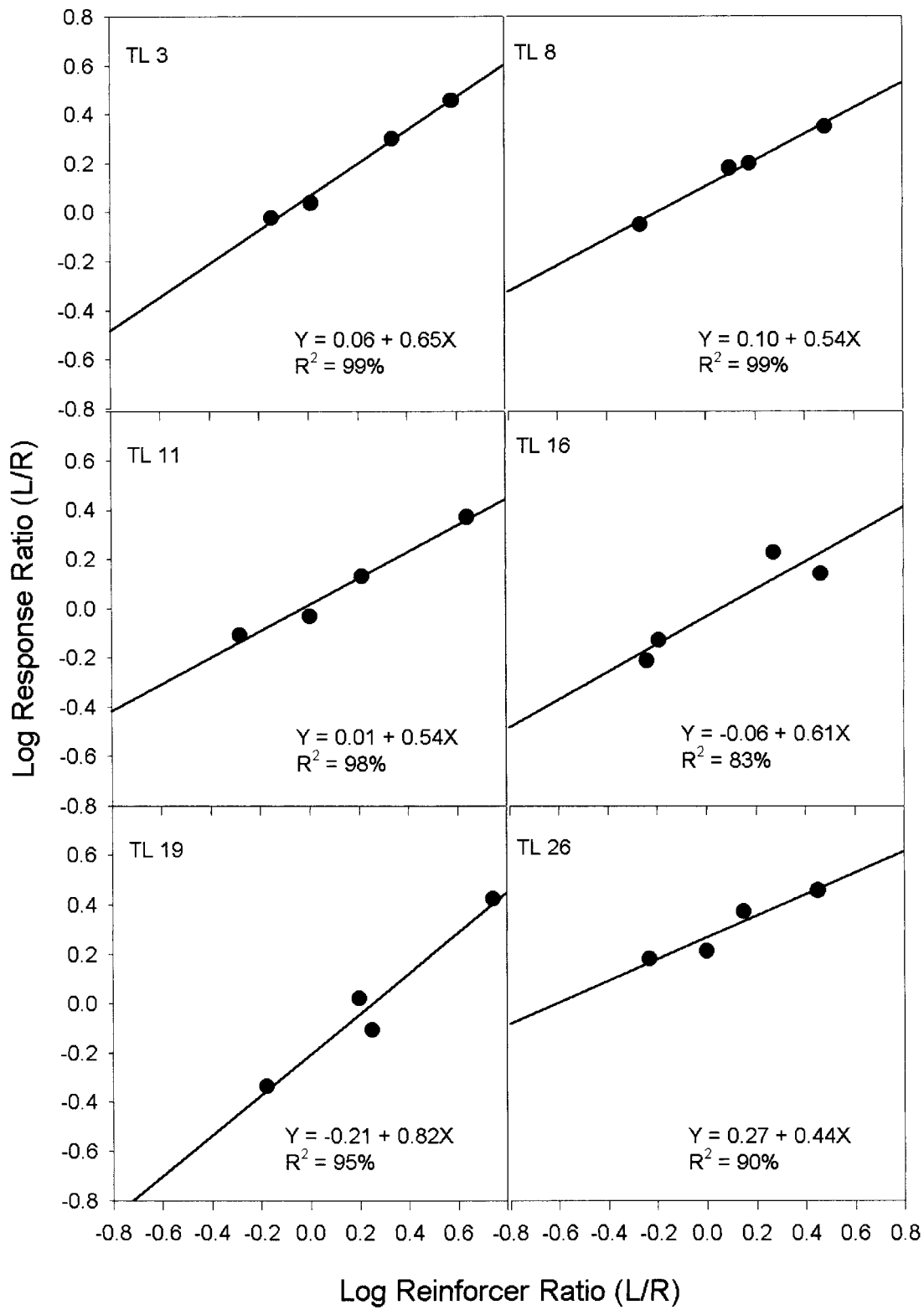
Wheel-running rates across schedules and between alternatives were compared using a repeated measures analysis of variance with schedule and side (left or right) as within-subject factors. According to this analysis, wheel-running rates did not differ by schedule, $F(3, 15) = 0.231$, $p > .10$, or by side, $F(1, 5) = 0.076$, $p > .10$; nor was there a significant Schedule \times Side interaction, $F(3, 15) = 1.270$, $p > .10$. Mean wheel-running rates for the left and right alternatives were 10.64 and 10.62 revolutions, respectively, per 15-s reinforcer.

DISCUSSION

The present investigation extended the generalized matching law to wheel-running reinforcement. Response and time allocation varied with the relative rates of obtained reinforcement. Undermatching was observed for both time and responses, which is a typi-

cal finding with most reinforcers (Baum, 1979; Wearden & Burgess, 1982); however, response allocation was systematically less sensitive to variation in relative rate of reinforcement than was time allocation. The results demonstrate that when reinforcers consist of periods of time during which a rat can run, the rats' responses are sensitive to the relative frequency with which alternatives provide those opportunities.

Three factors probably played a role in the present study: a low overall rate of response, a short COD duration, and long postreinforcement pauses. In general, the total number of responses allocated between the two alternatives was low. Overall response rates, calculated as total responses divided by total time allocated between the two alternatives, inclusive of postreinforcement pausing but exclusive of time of access to the reinforcer, for each rat by condition appear in Table 3. With the exception of Rat TL 26, response rates were low. For the other rats, mean response rates varied between 9.6 and 15.9 presses per minute. In contrast, TL 26 had an



average rate of 42.9 presses per minute. These rates are low compared to those usually observed for food-deprived rats pressing levers or food-deprived pigeons pecking keys on concurrent VI VI schedules of food reinforcement.

The second factor was the short COD duration. As Baum stated, "with no COD or too short a COD, preferences tend to fall short of matching, remaining too near indifference" (1974b, p. 232). That is, a high rate of switching between alternatives is associated with a lower sensitivity to differences in relative rates of reinforcement, and this lower sensitivity is reflected in slopes, for both time and response matching, less than 1.0. In the present study, the effect of too short a COD is probably most evident in the data from Rat TL 26. Of the 6 rats, TL 26 had both a high rate of responding and a high number of changeovers. On the left alternative, rates of responding for TL 26 across the different conditions varied between 48.6 and 56.4 presses per minute; on the right, rates varied between 25.2 and 34.8 presses per minute. The high rate of responding on the left alternative, which approached one press per second, suggests that postreinforcement pausing may have played less of a role in this animal's data, because pausing would have substantially lowered response rates. Changeover rates for TL 26 were calculated separately for each alternative as the number of changeovers to an alternative divided by the time allocated to that alternative. Rates varied between 9.6 and 13.2 changeovers per minute for the left alternative and 9.0 and 18.6 changeovers per minute on the right alternative. For this animal, slopes for both time and responses were low, as would be expected if the frequency of changing over was too high due to a short COD (Figures 1 and 2).

If, instead, one considers the percentage of total responses that were changeover responses, Rat TL 26 does not differ markedly from the other rats. Table 3 shows the percentage of total responses that were changeover responses for each condition for each rat.

About one fourth to one third of all responses were changeover responses. These responses were equally distributed between the two alternatives and contributed to undermatching by response ratios.

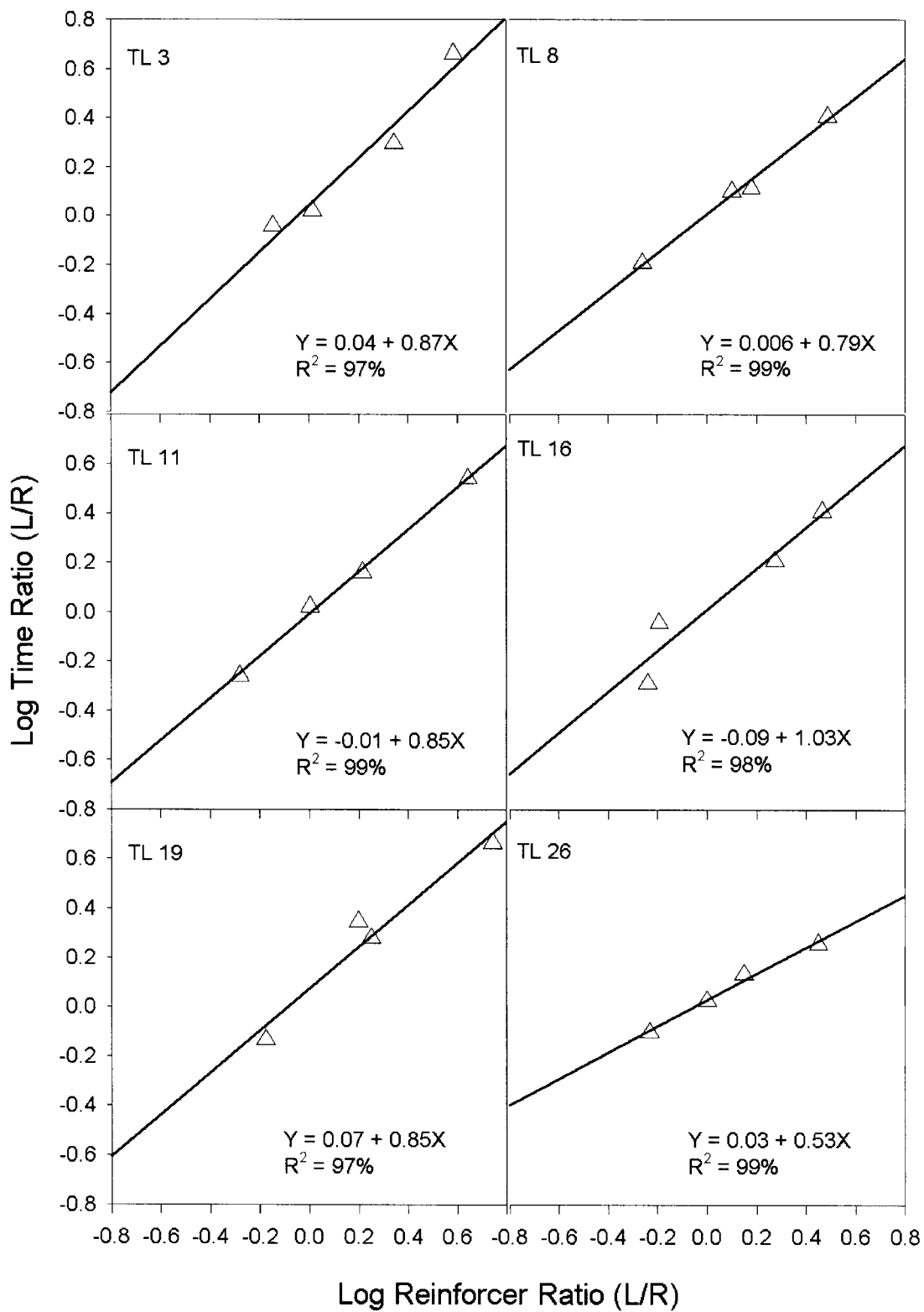
The third factor is postreinforcement pausing. Of the three factors, postreinforcement pausing is the most problematic for an assessment of matching. Long postreinforcement pausing has two effects. One is to interact with the interval schedules to produce undermatching for both response and time allocation. The other is to create the illusion of better time matching.

First, consider the case in which an animal obtains several reinforcers in succession from the same alternative without changing over. A long pause following each reinforcer would time out most, if not all, of the reinforcement interval, depending upon the schedule (all for short durations, most for longer). Consequently, the time remaining, during which responses would be allocated before the response that produced the next reinforcer, would be much shorter than would typically occur with more conventional reinforcers. Because richer schedules would be more affected than leaner schedules, response allocations would be driven closer to indifference.

Second, long pauses following reinforcement would make time allocation appear to be more sensitive to reinforcement allocation. If animals paused for a period of time following each reinforcer, then time spent pausing would be allocated to each alternative in accord with the relative rates of reinforcement obtained from each alternative. That is, each pause would be terminated with either a response to the same alternative or a response to the other alternative. Either way, an interval would be allocated to the alternative from which the reinforcement was obtained, and the distribution of pause times between the alternatives would have matched the distribution of reinforcers obtained from the two alternatives. Consequently, the contribution of postreinforcement pausing to

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Fig. 1. The logarithm of response ratio (left-right) as a function of the logarithm of the obtained reinforcer ratio for each rat. Straight lines were fitted to the data by the method of least squares to obtain values of a and $\log b$ in Equation 2. Estimates of the percentage of variance accounted for by log reinforcer ratio are also given.



time allocation would have produced better time than response matching. Furthermore, the magnitude of this effect would depend on the percentage of the total time allocated to pausing. The greater the percentage of time allocated to pausing, the better time matching would be relative to response matching.

Although postreinforcement pausing was not measured in the present study, Table 4 shows subsequent median and mean postreinforcement-pause durations on concurrent VI 60-s VI 60-s schedules of wheel-running reinforcement measured for 5 of the 6 rats used in the present study. (The 6th rat died in the interval following the completion of the present study.) Although not directly applicable to the present study, these data support the assertion that pausing occurred in the present study and may have played a role in the results. Specifically, Table 4 shows that, across animals, pausing represented 57% to 76% of the total time during which the concurrent schedule was in effect (i.e., session duration minus total reinforcement time). Thus, pausing represented a substantial proportion of the time being allocated between the two schedules.

Data from the present study are similar to those obtained by Foster et al. (1996) in their study of concurrent-schedule performance in dairy cows. In their first experiment, cows responded on concurrent VI schedules for crushed barley and meat meal as alternative reinforcers. The operant was the depression of a nose plate. COD duration was 3 s. Assessment of matching for time and responses showed severe undermatching for both measures; however, slopes for time allocation were greater for every animal. Response rates were low. Postreinforcement pauses of approximately 20 to 30 s occurred following each food delivery, and postreinforcement-pause ratios matched obtained reinforcement ratios. When postreinforcement-pause times were removed from measures of time allocation, slopes for net time allocation declined substantially. Mean slopes for time allocation inclusive and exclusive of postreinforcement

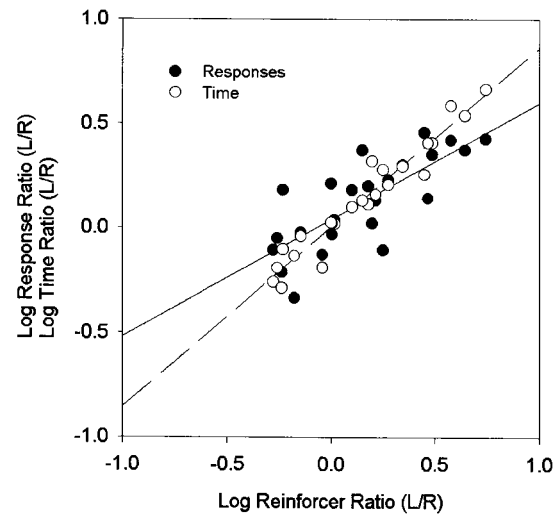


Fig. 3. Group data: the logarithm of response ratio (filled circles) and time ratio (open circles) as a function of the logarithm of the obtained reinforcer ratio. Straight lines were fitted to the data by the method of least squares to obtain values of a and $\log b$ in Equation 2 (see text).

pauses were 0.58 and 0.26, respectively. A similar reduction in slope for time allocation was observed in a second experiment with the same reinforcer on each alternative and a 5-s COD. When time spent in both food- and non-food-related other behaviors (i.e., other than plate pressing) was removed from time allocation, the average slope decreased from 0.53 to 0.24. Undermatching persisted despite a relatively long COD.

The removal of postreinforcement pausing from time allocation by Foster et al. (1996) removed the illusion of better time matching; however, the interaction of pausing with the interval schedules to produce undermatching remained. This would also account for the lack of a corrective effect of lengthening the COD from 3 to 5 s.

Table 5 shows the slopes that would result for responding in the present study if corrections for a low response rate and frequent changeovers were applied. To correct for low response rates, one response was subtracted from each alternative for every reinforcer ob-

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Fig. 2. The logarithm of time ratio (left-right) as a function of the logarithm of the obtained reinforcer ratio for each rat. Straight lines were fitted to the data by the method of least squares to obtain values of a and $\log b$ in Equation 2. Estimates of the percentage of variance accounted for by log reinforcer ratio are also given.

Table 3

Overall response rates (presses per minute) and percentage of total responses that were changeover responses for each concurrent VI VI schedule for each rat.

Rat	Concurrent				<i>M</i>
	VI 60 s	VI 48 s	VI 80 s	VI 30 s	
	VI 60 s	VI 72 s	VI 40 s	VI 90 s	
Overall response rate					
TL 3	12.6	13.4	11.3	11.3	13.2
TL 8	18.6	17.3	13.9	13.9	15.9
TL 11	11.1	9.1	7.4	7.4	9.6
TL 16	14.4	17.7	10.3	10.3	14.7
TL 19	8.7	12.7	6.2	6.2	10.8
TL 26	41.2	46.4	35.3	48.6	42.9
Percentage of total responses that were changeover responses					
TL 3	29	29	30	19	26.8
TL 8	37	36	36	36	36.3
TL 11	30	26	26	22	26.0
TL 16	27	21	26	21	23.8
TL 19	25	23	27	17	23.0
TL 26	32	24	29	28	28.3

tained from that alternative (Aparicio, 1999). To correct for frequent changeovers, one response was subtracted from each alternative for every changeover made from that alternative. Correcting for low response rates reduced slopes relative to the uncorrected response slopes. In contrast, correcting for frequent switching increased slope values and yielded slopes that, on average, approximated those obtained for time matching. Although this correction suggests that frequent switching between alternatives contributed to undermatching for responses, it does not rule

Table 5

Obtained slopes for time and response matching for each rat along with slopes for response matching for which response counts were corrected by subtracting reinforcers, by subtracting changeovers, and by subtracting both.

Rat	Uncorrected		Responses corrected by subtracting		
	Time	Responses	Reinforcers	Changeovers	Both
TL 3	0.87	0.65	0.59	0.87	0.84
TL 8	0.79	0.54	0.48	0.90	0.89
TL 11	0.85	0.54	0.46	0.72	0.65
TL 16	1.03	0.61	0.54	0.81	0.75
TL 19	0.85	0.82	0.75	1.09	1.07
TL 26	0.53	0.44	0.40	0.68	0.65
M	0.82	0.60	0.54	0.84	0.81

out the possibility that undermatching was due to pausing. Long postreinforcement pausing would similarly reduce response slopes, and this correction would not discriminate between these two sources.

In summary, the present study suggests that the generalized matching law (Baum, 1974b) can be applied to wheel-running reinforcement. Time and response allocations appeared to be sensitive to the relative rates of reinforcement obtained from two alternative sources. However, long postreinforcement pausing may produce the illusion of greater sensitivity of time allocation while at the same time interacting with the schedules, alone or in conjunction with frequent switching, to produce undermatching for responses. Thus, long postreinforcement pausing represents a serious source of error for assessing matching

Table 4

Median and mean postreinforcement pauses (in seconds) as well as the number of reinforcers obtained on each alternative on a concurrent VI 60-s VI 60-s schedule of wheel-running reinforcement with 30-s reinforcer durations on each alternative. Medians and means were obtained from the distributions of postreinforcement pauses over five consecutive sessions. The number of sessions (S) each animal was exposed to the schedule is also shown. The value in the final column is the mean percentage of the time during which the schedule was in effect that the animal was pausing following the reinforcer. Data are shown for all the rats except TL 19, which died in the interim.

Rat	Left			Right			S	%
	Median	Mean	n	Median	Mean	n		
TL 3	25.4	37.6	89	21.0	32.2	55	32	57
TL 8	46.1	78.6	24	80.6	96.0	63	21	76
TL 11	46.6	66.6	69	51.5	70.3	35	15	69
TL 16	36.8	48.6	88	32.2	44.5	48	30	70
TL 26	20.4	27.8	62	22.1	32.0	100	36	57

using standard concurrent VI VI schedules. Belke and Heyman (1994) used response-initiated VI schedules to control for the effect of postreinforcement pausing on interval schedules of short duration in their extension of the single-operant form of the matching law to wheel-running reinforcement. A similar approach may be required for an accurate assessment of matching with wheel-running reinforcement using concurrent interval schedules as well as any other situation in which long pauses follow the termination of a reinforcer.

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